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Dynamical Evolution Of Asteroid Pairs With Close Orbits

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Abstract. Dynamical evolution of paired asteroids sharing close orbits was investigated. Candidates were chosen from AstDyS database by Kholshevnikov metric value. Only 33 of 105 pairs with close orbits were associated as family members. Further orbit evolution modeling was performed by Orbit9 software. Each pair had 49 overall model scenarios due to different Yarkovsky drift values for semimajor axis. Close encounters between paired objects providing time estimations and feasible mechanisms of formation were evaluated. Uncertainties of Yarkovsky drift values affected orbit evolution and caused substantial distinctions in time formation evaluating. Dwarf planet Ceres and massive asteroids (Pallas, Vesta, etc.) perturbations should be taken into account and dynamical evolution research for asteroid pairs in close orbits under passing through resonances is considered in future numerical simulations.

INTRODUCTION

Dynamical evolution of asteroid pairs with close orbits has been researched for more than 10 years. Paper [1] suggests that paired asteroids with close orbital motion may have common origin. Pairs can be formed by collisional disruptions of massive asteroids. YORP-induced spin up may lead to rotational fission of fast spinning asteroids. In this case, the disparate fragment must exceed the escape velocity under the effect of the centrifugal force. Breakups of binary or multiple asteroid systems could also result in formation of paired asteroids with close orbits. BYORP effect is one of the mechanisms causing breakups of binaries or multiples. Incidental approaches of asteroid orbits should also be taken into account, notably for rich asteroid families, due to secular drift of semimajor axes affected by the Yarkovsky effect.

Examination of dynamical evolution of asteroid pairs with close orbits allows to estimate their ages [2–5]. If an asteroid pair has been produced by fragmentation, of particular interest are physyco-chemical properties of relatively young surface, which has had a brief contact with the space environment. Photometric observations are needed to probe these properties.

We implement KASPAR (**K**ourovka **As**teroid **Pa**irs **R**esearch) project at the Kourovka astronomical observatory of the Ural Federal University. Searching for asteroid pairs with close orbits, analysis of the link to the known asteroid families, numerical simulations of dynamical evolution of paired asteroids at various semimajor axis drift values under the Yarkovsky effect have been carried out within the project. This paper continues the studies in the papers [6, 7].

SEARCHING FOR ASTEROID PAIRS WITH CLOSE ORBITS

Distance estimations among orbits of numbered and observed in several oppositions asteroids were derived from AstDyS [8] database, which contained 647001 sets of orbit elements on the date 22/06/2018. We applied Kholshevnikov metrics to estimate the distances: ρ_2 (which is defined in 5-D space of the Kepler elements: p, e, i, Ω, g — latus rectum, eccentricity, inclination, longitude of the ascending node and argument of perihelion respectively; position on the orbit is not taken into account) and ρ_5 (which is defined in 3-D space of the elements p, e and i with all the possible values of Ω and g). We designate the metrics ρ_2 and ρ_5 in the same manner as Kholshevnikov *et al.* [9].

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We found 105 paired asteroids for which metric ρ_2 was no more than 0.002 (au)$^{1/2}$ and its square ρ_2^2 — 600 km. Asteroid pairs with the lowest values of the metric ρ_2 are shown in Table 1. The closest pair (63440) 2001 MD30 — (331993) 2004 TV14 belongs to (434) Hungaria family, which was formed by collisional disruption of the parent asteroid. The pair (229401) 2005 SU512 — 2005 UY97 belongs to (1547) Nele young family.

TABLE 1. Asteroid pairs with the lowest values ρ_2

ρ_2 [(au)$^{1/2}$]	ρ_5 [(au)$^{1/2}$]	ρ_2^2 [km]	ρ_5^2 [km]	Asteroids		Family
0.000034	0.000010	0.177	0.016	(63440) 2001 MD30	(331933) 2004 TV14	(434) Hungaria
0.000039	0.000038	0.230	0.211	(355258) 2007 LY4	(404118) 2013 AF40	—
0.000078	0.000066	0.916	0.645	(229401) 2005 SU152	2005 UY97	(1547) Nele
0.000106	0.000077	1.674	0.890	(356713) 2011 UK160	2014 QX220	—
0.000127	0.000115	2.426	1.981	(180906) 2005 KB6	(217266) 2003 YR67	—
0.000138	0.000053	2.866	0.424	(21436) Chaoyichi	(334916) 2003 YK39	—
0.000162	0.000153	3.905	3.513	(88259) 2001 HJ7	(337181) 1999 VA117	—
0.000176	0.000174	4.639	4.526	(53576) 2000 CS47	(421781) 2014 QG22	—
0.000228	0.000204	7.803	6.247	(87887) 2000 SS286	(415992) 2002 AT49	(93) Minerva
0.000317	0.000199	15.028	5.894	(346888) 2009 PB10	2002 CE266	—
0.000348	0.000106	18.095	1.692	(441762) 2009 CD39	(465401) 2008 GS110	—
0.000395	0.000218	23.287	7.089	(167405) 2003 WP118	2012 TK84	—
0.000403	0.000192	24.261	5.496	(341874) 2008 GB53	2012 TQ236	—
0.000409	0.000354	25.046	18.717	(320025) 2007 DT76	(489464) 2007 DP16	—
0.000436	0.000090	28.419	1.210	(143669) 2003 SO140	(506174) 2016 FH61	(434) Hungaria
0.000440	0.000264	28.960	10.401	(99052) 2001 ET15	(291788) 2006 KM53	—
0.000473	0.000463	33.433	32.064	(95750) 2003 ED28	(304873) 2007 RD148	—
0.000501	0.000396	37.570	23.399	(90265) 2003 CL5	2002 RH291	—
0.000505	0.000265	38.159	10.463	(348452) 2005 RU20	(418312) 2008 FF88	—
0.000513	0.000206	39.329	6.352	(224801) 2006 UQ127	(358983) 2008 SZ124	—
0.000568	0.000243	48.175	8.805	(17198) Gorjup	(229056) 2004 FC126	—
0.000584	0.000229	50.939	7.866	(76111) 2000 DK106	(354652) 2005 JY103	—
0.000590	0.000217	52.117	7.022	(267333) 2001 UZ193	2007 DY95	—
0.000603	0.000127	54.322	2.429	(4765) Wasserburg	(350716) 2001 XO105	(434) Hungaria
0.000603	0.000171	54.463	4.395	(11842) Kap'bos	(436415) 2011 AW46	—
0.000605	0.000356	54.694	18.908	(60151) 1999 UZ6	(338309) 2002 VR17	—
0.000611	0.000108	55.816	1.733	(178908) 2001 PD4	2010 XT2	—
0.000624	0.000093	58.182	1.305	(233771) 2008 TO124	(470785) 2008 UX299	—
0.000673	0.000505	67.647	38.071	(80218) 1999 VO123	(213471) 2002 ES90	—
0.000687	0.000080	70.638	0.962	(32957) 1996 HX20	(38707) 2000 QK89	—
0.000698	0.000422	72.771	26.682	(145113) 2005 GH123	2017 FS47	—
0.000752	0.000144	84.648	3.092	(1270) Datura	(433382) 2013 ST71	—
0.000759	0.000528	86.174	41.663	(55913) 1998 FL12	2005 GQ107	—
0.000766	0.000407	87.734	24.724	(133302) 2003 SM45	(458905) 2011 UE230	(20) Massalia
0.000773	0.000342	89.293	17.443	(178996) 2001 RY5	2011 CB22	(434) Hungaria

Figure 1 shows the positions of the paired asteroids with close orbits with respect to asteroid families. Family asteroids are indicated by dots and pairs associated with families — by big orange spheres. Smaller brown spheres show pairs not associated with any family. AstDyS database was used to identify the pairs with the families and to classify the families by the type on the basis of the papers [10–14].

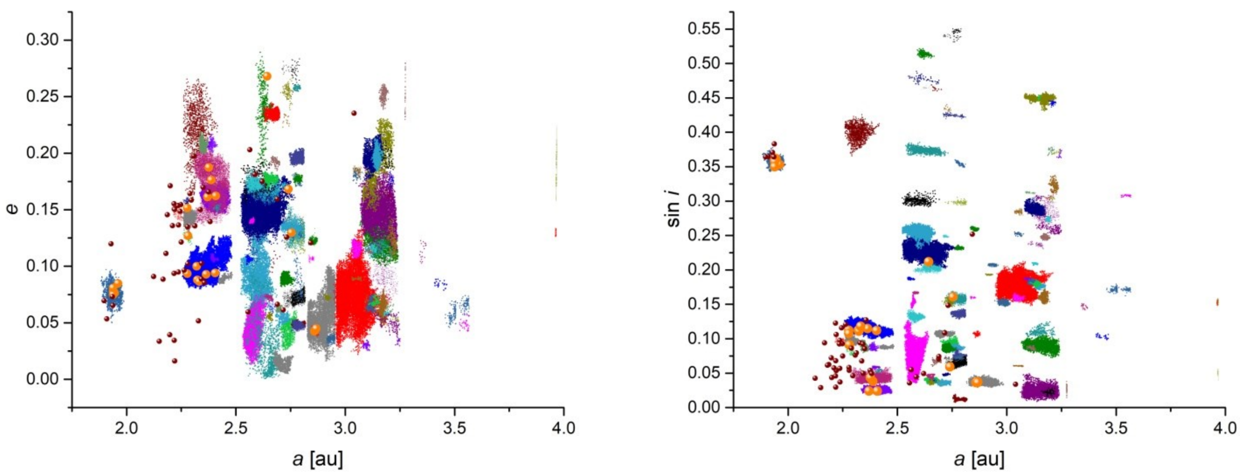

FIGURE 1. Asteroid pairs and families on the (a — e) and (a — sin i) planes

We identified 33 of 105 paired asteroids with close orbits with the asteroid families, meanwhile, 16 of them were associated with families formed by fragmentation of the parent asteroid: 10 pairs belonged to (158) Koronis and 6 pairs — to (434) Hungaria. Furthermore, 10 pairs were belonging to families created by ejections as a result of collisional crater formations on the ancestor asteroid: 7 pairs to (4) Vesta, 2 pairs to (20) Massalia and a pair to (15) Eunomia. Young families (396) Aeolia and (1547) Nele both kept one pair, as well as (93) Minerva family characterized by one-sided V-diagram. In addition, 4 of the pairs are the members of unclassified families: (135) Hertha with 2 pairs, (298) Baptistina and (1388) Duponta each with a pair.

Remaining 72 pairs of asteroid with close orbits were not identified with any known asteroid families.

Semimajor axes of asteroid orbits belonging to the close pairs did not exceed 3.1 au. Most of the pairs shared semimajor axes range 1.9–2.5 au, which may occur due to selection effect. One of the pair members typically was small and thereby faint.

ORBIT EVOLUTION MODELING

We performed numerical simulations of orbital evolution for asteroids to find close encounters between paired objects and estimate the conditions of such approaches. For this purpose, the equations of motion were integrated within 20 000 yr interval in the past by Orbit9 software as a part of OrbFit [15] package. Initial orbital elements were chosen from AstDyS database for T_0 = MJD58000 (4 September 2017). Equations of motion for asteroids, 8 major planets and Pluto dwarf planet were integrated simultaneously.

Del Vigna *et al.* [16] evaluated the limit of the semimajor axis drift order of magnitude caused by the Yarkovsky effect as $1 \cdot 10^{-3}$ au/Myr for most near-Earth asteroids. Likewise, Carruba, Vokrouhlický, and Nesvorný [17] showed that the drift magnitude maximum was not exceeding $1 \cdot 10^{-3}$ au/Myr for Veritas family asteroids. Hence, as the orbits of the paired asteroids considered in this paper were located between the above-mentioned dynamical regions, we pursued 7 orbital evolution scenarios with various semimajor axis drift: 0 (without drift), $\pm 1 \cdot 10^{-5}$, $\pm 1 \cdot 10^{-4}$ and $\pm 1 \cdot 10^{-3}$ au/Myr.

We analyzed 49 orbital evolution scenarios for each pair. If a close encounter was detected, we estimated its parameters: time interval $\Delta t_{\min}$ with regard to T_0 epoch, distance between asteroids $\Delta r_{\min}$ and their relative velocity $\Delta v_{\min}$. Table 2 shows approach conditions for paired asteroids (355258) 2007LY4 — (404118) 2013 AF40. It is noticeable that the encounter parameters of paired asteroids greatly depend on the absolute value of the drift as well as on its sign.

TABLE 2. Approach conditions of (355258) 2007 LY4 — (404118) 2013 AF40 asteroid pair

355258	Parameters	404118		
da/dt [au/Myr]		da/dt [au/Myr]		
		0	$1 \cdot 10^{-5}$	$-1 \cdot 10^{-5}$
0	Δt_{min} [yr] Δr_{min} [km] Δv_{min} [cm/s]	5824.8 2161 4.0	5806.2 1702 4.5	5842.6 1731 4.0
$1 \cdot 10^{-5}$	Δt_{min} [yr] Δr_{min} [km] Δv_{min} [cm/s]	5842.4 1914 5.6	5824.8 2071 4.2	5861.4 2380 4.9
$-1 \cdot 10^{-5}$	Δt_{min} [yr] Δr_{min} [km] Δv_{min} [cm/s]	5806.4 1641 3.4	5789.0 2503 5.7	5824.8 2233 3.8

ASTEROID PAIRS IN THE VICINITY OF RESONANCES

Resonant scattering of asteroids under passing through the resonances (mean-motion and secular) is one of the mechanisms producing Near-Earth Asteroids (NEAs) [18]. However, no paired asteroids with close orbits among NEAs have been discovered. Gravitational scattering of asteroid pairs over inner planets due to secular semimajor axis drift towards vicinities of resonances may produce the absence of close pairs.

We searched for such pairs in the vicinities of jovian mean-motion resonances 1:4, 1:3, 2:5 and 3:7 (located at 2.06, 2.50, 2.82 and 2.96 au respectively). Selected pairs are shown in Tables 3 and 4. We listed objects including three pairs on either side of each resonance.

TABLE 3. Asteroid pairs near jovian mean motion resonances 1:4 and 1:3

ρ_2 [(au)$^{1/2}$]	ρ_5 [(au)$^{1/2}$]	ρ_2^2 [km]	ρ_5^2 [km]	Asteroids		Semimajor axes [au]	
				Vicinity of 1:4 resonance			
0.120050	0.000929	2156000	129.0	2015 FZ331	2017 DE15	1.9872	1.9857
0.155420	0.000506	3613600	38.3	(218550) 2005 BQ26	(505010) 2011 OH15	1.9946	1.9945
0.199180	0.000872	5935000	113.7	(441313) 2008 AX83	(467916) 2011 OA14	2.0003	2.0023
0.000888	0.000467	118	32.6	(184300) 2005 ED114	(422777) 2001 UU227	2.1244	2.1242
0.122719	0.000581	2253000	50.5	(371832) 2007 VJ230	2015 KQ23	2.1376	2.1360
0.203031	0.000756	6166600	85.5	(174669) 2003 SY246	2015 TA291	2.1433	2.1413
				Vicinity of 1:3 resonance			
0.080443	0.000735	968070	80.8	(114610) 2003 DN8	2007 CS12	2.4865	2.4859
0.239192	0.000936	8558900	131.2	(34991) 4295T-3	(142610) 2002 TU132	2.4865	2.4841
0.109126	0.000491	1781500	36.1	(381833) 2009 WL27	(463437) 2013 MO4	2.4879	2.4867
0.134450	0.000515	2704300	39.7	(119332) 2001 SA140	(156388) 2001 YE101	2.5106	2.5093
0.070787	0.000672	749600	67.5	(347020) 2010 EV20	(401423) 2013 CX82	2.5109	2.5128
0.145184	0.000823	3153300	101.4	(307726) 2003 UM176	(398159) 2010 FU11	2.5134	2.5131

ρ_2 $[(au)^{1/2}]$	ρ_5 $[(au)^{1/2}]$	ρ_2^2 [km]	ρ_5^2 [km]	Asteroids		Semimajor axes [au]	
Vicinity of 2:5 resonance							
0.282895	0.000821	11972000	100.8	(323994) 2005 UB234	2014 UE168	2.8159	2.8151
0.335230	0.000858	16812000	110.1	(261361) 2005 UF319	(446464) 2014 JK72	2.8162	2.8161
0.226279	0.000828	7659700	102.5	2014 JK86	2015 TW218	2.8178	2.8161
0.102627	0.000606	1575600	54.9	(388731) 2007 VY242	(468224) 2015 BG132	2.8288	2.8287
0.106499	0.000843	1696800	106.3	(55288) 2001 SZ30	(157663) 2005 YB53	2.8298	2.8274
0.224301	0.000627	7526400	58.9	(33153) 1998 DH15	(60524) 2000 EA40	2.8306	2.8307
Vicinity of 3:7 resonance							
0.143784	0.000593	3092800	52.5	(15414) Pettirossi	(140739) 2001 UZ104	2.9526	2.9531
0.070337	0.000978	740100	143.0	(422509) 2014 TP5	2014 WX533	2.9535	2.9520
0.116597	0.000463	2033800	32.1	(97059) 1999 VU3	(260302) 2004 TK117	2.9541	2.9526
0.602428	0.000276	54292000	11.4	(408341) 2013 GR79	(467669) 2008 UH116	2.9594	2.9591
0.529204	0.000382	41896000	21.8	(117494) 2005 CU19	(140958) 2001 VT103	2.9602	2.9612
0.508237	0.000867	38642000	112.5	(76239) 2000 EF82	(273125) 2006 GR11	2.9615	2.9610

TABLE 4. Asteroid pairs near jovian mean motion resonances 2:5 and 3:7

RESULTS AND DISCUSSION

Orbit evolution modeling of paired asteroids provides information about dynamics of the objects at the moments of close encounters, age of pairs, and, perhaps, the mechanisms of their formation: collisional disruption, YORP-fission, binary or multiple breakup, incidental approach, etc. Accurate evaluation of past approach conditions between asteroids sharing close orbits requires additional awareness of their sizes, shapes, spin axes obliquity, surface thermal properties, etc. Intense positional and photometrical observations of asteroid pairs are needed for this task [6, 7]. Such observations could be implemented within KASPAR project.

Substantial differences between close encounter time estimations of paired asteroids may arise from semimajor axis Yarkovsky drift uncertainties [6]. Fig. 2 shows evolution scenarios of distance Δr between (229401) 2005 SU152 — 2005 UY97 asteroid pair.

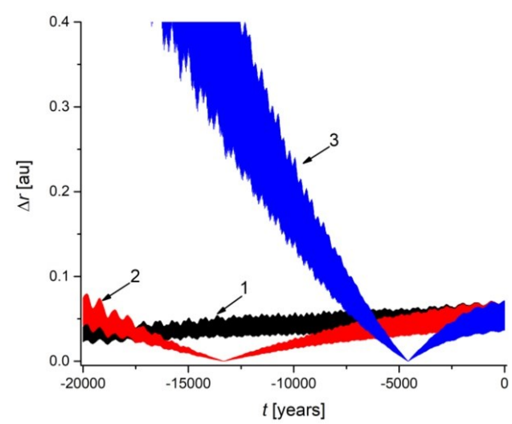

FIGURE 2. Evolution scenarios of distance between (229401) 2005 SU152 — 2005 UY97

Curve 1 in Fig. 2 corresponds to the evolution scenario without taking into account Yarkovsky effect. Close approach occurs beyond considered time interval 20 000 yr in this case. Curve 2 is consistent with da/dt values $1 \cdot 10^{-4}$ and $-1 \cdot 10^{-4}$ au/Myr respectively. We estimated approach parameters $\Delta t_{\min}$ = 13 324.4 yr, $\Delta r_{\min}$ = 133 km and $\Delta v_{\min}$ = 2.7 cm/s. Curve 3 conforms to drift values $1 \cdot 10^{-3}$ and $-1 \cdot 10^{-3}$ au/Myr respectively, $\Delta t_{\min}$ = 4 577.2 yr, $\Delta r_{\min}$ = 2 205 km and $\Delta v_{\min}$ = 7.3 cm/s.

Since the detected pairs are located in the main belt, dwarf planet Ceres and massive asteroids (Pallas, Vesta, etc.) perturbations should be taken into account in future numerical simulations. Dynamical evolution research for asteroid pairs in close orbits under passing through resonances should be also considered in the future.

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